# F. Durability of Diesel Engine Component Materials

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## Objectives

- Provide test data, analyses, and models that enable the use of durable, lower-friction moving parts in diesel engines in heavy-vehicle propulsion systems.
- Develop test methods that simulate the environment of scuffing-prone engine parts.
- Conduct structural and tribological characterizations of promising new materials, surface treatments, composites, and coatings.

## Approach

- Identify and focus on diesel engine components that require durability and low-friction behavior and might benefit from advanced materials. These include (a) wastegate bushings for exhaust gas recirculation (EGR) components and (b) fuel injector components.
- Identify materials, coatings, and/or surface treatments that have the potential to increase the durability of the selected engine components.
- Develop test methods to evaluate and quantify the performance of candidate materials under simulated use conditions.
- Develop graphical methods and models to portray the effects of operating parameters, like speed, load, and surface finish, on the scuffing response of the materials.

## Accomplishments

- Designed, built, and used a high-temperature oscillatory scuffing test system that operates at wastegate bushing temperatures (~600–700$^{o}$C).
- Published results of tests on a range of metallic alloys, ceramics, and coatings to determine which of these had the best durability under high-temperature conditions.
- Developed a novel, 'pin-on-twin' scuffing test to evaluate fuel injector materials in diesel fuel and low-sulfur fuel environments.

- Developed criteria for the onset of scuffing damage and evaluated traditional steel fuel injector materials as well as ceramics, advanced cermets, and hard coatings in diesel fuel and low-sulfur fuel. Represented results in terms of 'scuffing maps' and transition diagrams.
- Developed a model for scuffing tendency that considers lubricant characteristics and solid material characteristics. Prepared a final report that explains the model and its rationale.

## Future Direction

- The focus on fuel systems and exhaust gas recirculation (EGR) components ended in FY 2005. It will be succeeded by a new effort that focuses on valve train durability issues.

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**Introduction**

The diesel engine industry continues to face the important challenge of improving fuel efficiency while meeting increasingly strict emissions regulations. These challenges are being addressed by modifying engine designs and control systems and by developing exhaust gas after-treatments. Such modifications affect the mechanical, thermal, and chemical environments in which the engine materials must operate, and currently used materials may fall short of meeting these needs. New materials are needed to enable new technological goals.

The objective of this effort is to enable the selection and use of durable, lower-friction moving parts in diesel engines for heavy-vehicle propulsion systems through the systematic evaluation of promising new materials, surface treatments, composites, and coating technologies. The current approach involves developing test methods, analyzing microstructures of candidate materials, developing design maps with variables like surface finish and frictional behavior, and modeling the damage process itself. The focus on exhaust gas recirculation (EGR) components and fuel injector plungers was based on discussions with diesel engine manufacturers. Before developing tests to evaluate materials for improved durability, it was necessary to conduct a tribosystem analysis to understand the conditions under which the surfaces of these components operate in a diesel engine. The nature of contact damage on engine components was reviewed to ensure that laboratory test methods would adequately reproduce that kind of damage. Then suitable tests were developed, surface damage and friction data were analyzed, and modeling tasks were undertaken.

**Approach**

In FY 2001, and based on the definition of several key durability problems, a test method and apparatus were developed to study the high-temperature friction and wear characteristics of candidate EGR system materials. That methodology has seen continued use for evaluating metal alloys, ceramics, coatings and other experimental materials for moving parts in waste gate bushings. In FY 2002, the effort was extended to include an investigation of the scuffing of fuel injector component materials. Laboratory tests were developed and refined to produce and measure the type of fine-scale surface damage that is observed in fuel system parts. In FY 2003, research continued in two areas: (1) evaluating the effects of diesel fuel sulfur reductions on scuffing and (2) identifying materials and coatings for high-temperature scuffing resistance in EGR components. During FY 2004, a three-dimensional 'scuffing map' was developed to depict conditions for scuffing initiation and propagation in time and space domains. By the end of FY 2004 a new scuffing model, one that integrates boundary film characteristics with material properties, had been proposed. The model recognizes the complexities of reciprocating sliding in which velocity is continually changing and the direction of motion reverses periodically. In FY 2005 the model was refined and improved to consider optimization of surface finish and the role of abrasion in reducing the tendency for materials to adhere to one another.

**Results**

The results presented here are an abbreviated version of a more detailed final report. A milestone report, dated March 2004, described the reciprocating sliding experiments in which results led to the conceptual framework for the three-regime model for scuffing. That model considers the failure of a lubricating film and the increased deformation of the contact surfaces to produce progressively severe surface damage. It represents an interdisciplinary approach and integrates concepts from both lubrication theory and materials science. The model, schematically shown in Figure 1, uses three submodels whose applicability depends on whether the contact is effectively lubricated (solid surfaces that are not touching), boundary-lubricated, or subjected to significant solid contact and plastic deformation. The higher the contact pressure, the less likely the lubricant will effectively separate the moving surfaces and the other regimes will come into play.

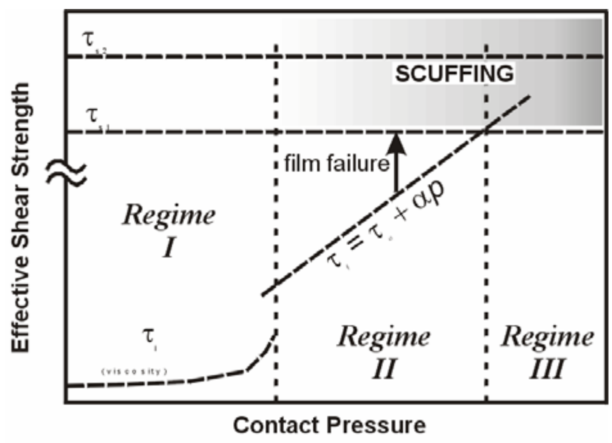


**Figure 1.** The scuffing model can be represented in three distinct regimes depending on the relative roles played by the liquid lubricant (I), thin boundary films (II), and the contacting solids (III).

Conceptually, the horizontal axis, labeled 'Contact Pressure' in Figure 1, can also be used to represent time. First, there is a period of effective operation whose duration depends on the nature of the materials, mechanical design and operating parameters, surface finish, and the regime of lubrication. Parts can perform very effectively in Regime I for millions of cycles if all goes well. However, the system can also operate in a boundary lubrication regime (II) in which some contact occurs.

As components and lubricants age, or if the contact pressure is too large to sustain a full film condition, then Regime I may either be finite in length or not observed at all, and the system may find itself in Regime II, which is governed by the thin boundary films that form from species initially present in the lubricant (or fuel). One can indirectly monitor the stability of the shear strength of interfacial films by observing the time-dependence of the friction coefficient. If the duration of contact is expressed in terms of numbers of oscillating cycles, as in a fuel injector plunger, then the transition from Regime I to Regime II can be expressed as follows:

$$\mu_x = \mu_{ff} + \Delta\mu\left(\frac{x}{L}\right)^n \quad , \tag{1}$$

where $\mu_x$ = friction coefficient at $x$ cycles, $\mu_{ff}$ = friction coefficient for full-film lubrication, $\Delta\mu$ = the change in friction during the transition from full-film to boundary lubrication, $x$ = current number of oscillating cycles, $L$ = number of cycles to reach Regime II, and $n$ = a constant that reflects the rate of change during the transition period. In Eq. (1), the change in friction during the transition is simply

$$\Delta\mu = \mu_{bl} - \mu_{ff} \quad , \tag{2}$$

where $\mu_{bl}$ = the friction coefficient for boundary lubrication at the start of Regime II. Assigning typical values of $\mu_{ff}$ = 0.01, $\mu_{bl}$ = 0.12, and letting $L$ = 1,000,000 cycles, we can plot Eq. (1) for a finite life in Regime I for several values of $n$ (see Figure 2). The greater the magnitude of the rate constant ($n$), the longer is the incubation period, but the more rapid the transition.

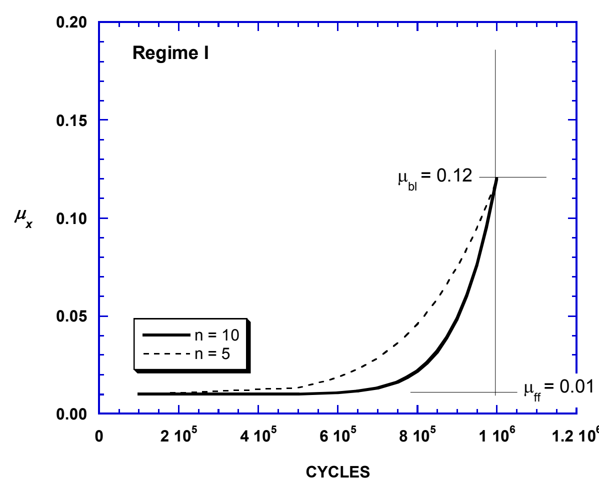


**Figure 2.** Portrayal of a finite-length Regime I with various transition rates.

Physically, the exponent *n* in Eq. (1) reflects such processes as a loss in lubricant load carrying capacity from oxidation or degradation of the additive package (in closed systems), a change in the contamination level in the system due to debris buildup or contaminant entrainment, or even phase-transformation-induced swelling of the plunger material to reduce bore clearance and increase surface contact. The referenced final report describes a second submodel for the localized changes in the composite surface roughness of the contact as scuffing initiates and propagates from the ends of the reciprocating stroke to its midpoint.

A smooth, hard material may work very well sliding against a soft counterface as long as the adhesion of the latter can be mitigated by a lubricating boundary film. That can only happen if there is sufficient clearance in the plunger bore to enable the formation of such a film.

Light abrasion can prevent the buildup of adhesive patches (transfer layers). In the absence of significant adhesion (reduced by lubrication), a factor that indicates the tendency for abrasion (AT) can be defined as

$$\mathrm{AT} = S\frac{H_h}{1.2H_s} \quad , \tag{3}$$

where $H_h$ = the scratch hardness of the harder side, $H_S$, = the scratch hardness of the softer side, and $S$ = the deviation from the optimal roughness. The factor 1.2 enters because of classic work by David Tabor (ca. 1951) on hardness that suggests for many materials, there must be about 20% difference in hardness in order for abrasion to occur. The deviation from the optimum surface roughness can be defined as

$$S = \left|R_h - R_{opt}\right|^m \quad , \tag{4}$$

where $R_h$ = the roughness of the harder surface, $R_{opt}$ = the optimal roughness (determined by experiments), and $m$ = a weighting factor for the importance of this function Reciprocating scuffing test data for a series of materials were used to evaluate scuffing based on the foregoing relationships. This work showed an optimal roughness of about 0.07 µm for the given tribosystem and indicated values for the time to initiate scuffing.

The AT parameter is plotted vs the initiation period for various materials against 52100 steel (including zirconia, TiN hard coatings, $Ni_3Al$ bonded cermets, and 52100 steel itself) in low-sulfur fuel in Figure 3. A linear fit to the data, excluding the self-mated steel, was quite good (R = 0.931). The implications of the relationship may initially seem counterintuitive because the more abrasive (i.e., the higher the AT parameter), the longer the period for the onset of scuffing. Closer consideration of the physical situation, however, suggests that scuffing is controlled by adhesive processes, and if abrasion of the surface prevents the formation of adhesive bonds, then a small amount of abrasion can in effect retard the onset of scuffing. Adhesion is promoted by self-mated materials, like the case for 52100 steel, and therefore, the circled data in Figure 3 show a markedly reduced resistance to the onset of scuffing. Adhesion also promotes the transfer of soft material than can fill up valleys in the surface that might otherwise serve as lubricant reservoirs. While a modicum of abrasion may be good for scuffing reduction, too much abrasion could result in an unacceptably high degree of abrasive wear damage and an unacceptable loss of clearance between mating parts. Therefore, there must be a balance between effective boundary lubrication and the light abrasiveness of optimally rough surfaces to avoid adhesive contact.

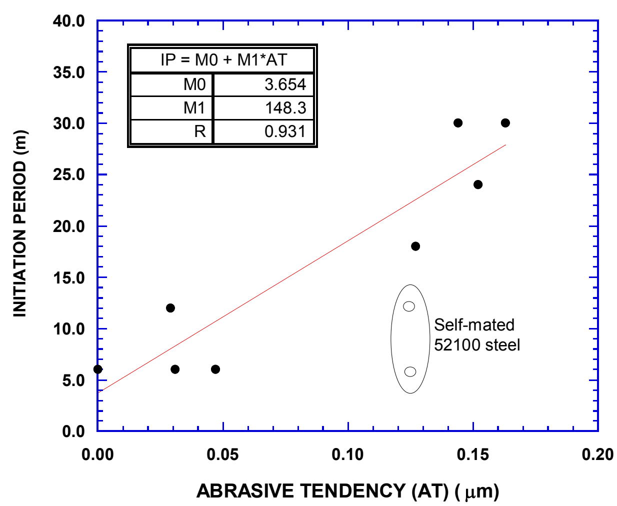


**Figure 3.** Relationship between the AT parameter and the initiation period for scuffing in reciprocating sliding in Jet A, low-sulfur fuel.

## Summary and Conclusions

- The 3-D friction-scuffing maps can be developed to depict scuffing initiation in both time and space domains. These maps can be used to construct scuffing transition diagrams that correlate scuffing resistance to surface finish and sliding velocity.
- Current and candidate fuel injector material combinations seem to exhibit an optimum surface finish (neither too smooth nor too rough), which can extend the times to initiate and propagate scuffing damage. The optimum surface finish is a function of the geometric conditions, the normal load, the characteristics of the fluid film that is trapped in the valleys of the surface roughness, and the adhesion characteristics of the mating surfaces.
- Abrasion can play a subtle role in avoiding adhesive junction formation. Therefore, harder/softer material combinations (like zirconia on steel) can be successful in scuffing-sensitive applications. That works if the surface finish is optimized and abrasion is kept to a minimum.
- A new scuffing model was developed and reported.

## Presentations and Publications

P. J. Blau, "Challenges for the application of engineered surfaces to tribosystems with multiple contact modes," invited presentation at the symposium on Integrated Surface Engineering, ASME/STLE Tribology Conference, Ponte Vedra, Florida, October 28, 2003.

P. J. Blau, J. J. Truhan, and J. Qu, "*Scuffing Transition Diagrams for Fuel Injection System Materials*, Project Milestone Report, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2004.

P. J. Blau, J. Qu, and J. J. Truhan, *On the Definition and Mechanisms of Scuffing in Fuel System Components—An Integrated Process Model*, Project Milestone Report, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 2004.

J. Qu, J. J. Truhan, and P. J. Blau, "Detecting the Onset of Localized Scuffing with the Pin-on-Twin Fuel-Lubricated Test for Heavy Duty Diesel Fuel Injectors," *SAE International Journal of Engine Research*, **6**(1), 1–9 (2005).

J. Qu, J. J. Truhan, and P. J. Blau, "Evaluating Candidate Materials for Heavy Duty Diesel Fuel Injectors Using a 'Pin-On-Twin' Scuffing Test," *Tribology International*, **38**(4), 381–390 (2005).

P. J. Blau, J. Qu, and J. J. Truhan, "A Multi-Stage Model for Scuffing of Reciprocating Components with Special Consideration of Fuel Injector Plungers," Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 30, 2005 (in press).